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MEASUREMENT OF CARBON DIOXIDE ACCUMULATION AND  
PHYSIOLOGICAL FUNCTION IN THE LAUNCH AND ENTRY AND  
ADVANCED CREW ESCAPE SUITS

Final Report

NASA/ASEE Summer Faculty Fellowship Program--1996  
Johnson Space Center

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JSC Colleague: M.C. Greenisen  
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## ABSTRACT

The Launch and Entry Suit (LES) and Advanced Crew Escape Suit (ACES) are worn by astronauts for launch and entry. Previous work by Waligora, et al., 1992, Waligora and Gilbert, 1992, and Dalrymple 1996, have found that carbon dioxide (CO<sub>2</sub>) accumulation in the LES/ACES helmet may be problematic. CO<sub>2</sub> accumulation is important because high inspired levels of CO<sub>2</sub> reduce physical function and pose a safety hazard (e.g. levels of CO<sub>2</sub> accumulation of 3.6% in the Extravehicular Mobility Unit are sufficient to terminate Extra Vehicular Activities). My task was to design a suitable test protocol for determining the important physiological aspects of LES/ACES use. Three basic issues arose. First was the determination of the astronaut's CO<sub>2</sub> inspiration during visor-down use at rest and during walking at 3.5 mph. A sub-issue was the impact of a pneumotach on CO<sub>2</sub> since it has been previously observed that when the Aerosport pneumotach was used, performance seemed improved, which might be attributable to a lowered respiration rate when using the pneumotach. The second issue was the energy costs of walking in the LES/ACES with various G-suit inflation levels, since G-suit inflation increases metabolic costs and metabolic costs influence the CO<sub>2</sub> production in the LES/ACES helmet. Since G-suit inflation improves orthostatic tolerance after space flight, but likely increases the energy costs of walking, the balance between G-suit inflation and CO<sub>2</sub> accumulation is an important safety consideration. The third issue which arose from pilot work was the substantial reduction in physical function after a 10 min visor-down period prior to walk.

## INTRODUCTION

In the event of an emergency egress after landing, the LES/ACES serves as a protective garment and together with the integrated Emergency Oxygen Supply (EOS) provides safe breathing air. Should a contingency egress be necessary, crew members exit the space craft with the helmet visor down, breathing 100% O<sub>2</sub> from the EOS and walk/run a distance of 400 meters upwind from the vehicle. Previously, a pilot study determined the CO<sub>2</sub> distribution pattern in the non-conformal helmet under simulated emergency egress conditions. During this study, subjects wore the LES with G-suit inflated to 1.5 psi and visor down, inspiring 100% O<sub>2</sub>, while attempting a 5 min walk at 3.5 mph on a treadmill (equivalent to 400 meters).

Those pilot study results showed CO<sub>2</sub> build-up in the helmet occasionally exceeded 7.5%. Three of five subjects were unable to complete the 5 min walk. Three subjects complained of O<sub>2</sub> starvation during the study. These results agree with previous unpublished findings by Waligora, et al. 1992, Waligora and Gilbert, 1992, who in preliminary tests found that carbon dioxide (CO<sub>2</sub>) accumulation in the both conformal and non-conformal helmets could be problematic. Based on the results of these pilot studies, a follow-up study is proposed. The prior studies suggested there was a potential problem with CO<sub>2</sub> accumulation, but did not compare the Aerosport pneumotach, and did not examine the impact of seated rest immediately before the walk. The 6 min seated rest would represent the best-case scenario since nominal landing procedures at Kennedy Space Center (KSC) require visor-down above a flight altitude of 10k feet (NASA Shuttle entry key cards, NASA Doc. #48019).

## OBJECTIVES

To determine if the inspired CO<sub>2</sub> levels are within acceptable ranges during simulated landing and contingency egress:

- 1) What is the % CO<sub>2</sub> inspired and expired while:
  - a) seated quietly for 6 min, visor down, in the LES/ACES (simulating emergency approach and landing period) while breathing 100% O<sub>2</sub>?
  - b) treadmill walking at 3.5 MPH for 5 min while wearing the LES/ACES ensemble and breathing 100% O<sub>2</sub>?
- 2) What is the % CO<sub>2</sub> inspired and expired during above simulated egress conditions breathing through the Aerosport pneumotach in a manner similar to the Crew Transport Vehicle Locomotion Egress study, Detailed Supplemental Objective (DSO) 331. Observations suggest that the pneumotach affects respiration and gas mixing within the helmet, resulting in lower CO<sub>2</sub> inspiration.
- 3) How does the G-suit inflation level affect the energy costs of walking at 3.5 mph (5.6 km/hr), 0% grade? (Appropriate use of the G-suit during ambulation can only be determined by evaluating the costs and benefits of various G-suit inflations during ambulation).
- 4) What is the impact on performance of a 6 minute visor-down period prior to the walk (simulation of nominal landing procedures at KSC)? And how does a 6 min visor-down rest period affect performance in an immediately succeeding 5 min walk at 3.5 mph (similar to DSO 331 with a simulation of visor-down above 10k feet as per NASA Shuttle entry key cards, NASA Doc. #48019).

## METHODS

- 1) Subjects N=12 with physical characteristics similar to the Astronaut Corps will be drawn from the Exercise Countermeasures Project and Crew and Thermal Systems Division.
- 2) Six subjects will be evaluated on each test day. For example, 3 subjects will be tested with the G-suit inflated to 3 clicks (1.5 psi) and the other half at 0 clicks (each "click" adds 0.5 psi pressure to the G suit).

3) Another set of six subjects will be completed on a successive day; half of the subjects will be tested at 3 clicks of G-suit inflation (1.5 psi) and the other half at 0 clicks. All G-suit inflation levels will be counterbalanced to avoid ordering effects.

4) On subsequent test days, subjects will be retested in untested G-suit configurations and rest/walk sequencing (i.e. a crossover design). This will give us some test-retest reliability information because some aspects of the test such as seated rest in the LES/ACES will be replicated exactly.

Goal -- at least 10-12 subjects completed in a month.

#### Test Protocol

1) Subject will be weighed and instrumented with a heart rate (HR) monitor, skin and rectal thermocouples and then will don the LES/ACES. Subject will don a specially configured LES/ACES helmet with one CO<sub>2</sub> sampling capillary located on the microphone boom of the communications headgear as close as practical to the mouth/nose routed through the special Aerosport helmet adapter (with the other adapter openings sealed). Or, for Aerosport pneumotach tests, a sampling capillary will be located at the pneumotach opening to determine the impact of the pneumotach on inspired CO<sub>2</sub>. This is needed to determine the influence of the pneumotach since it has been observed that the pneumotach appears to positively influence the visor-down walk ventilatory performance. This measure could lead to a solution to anticipated high inspired CO<sub>2</sub> levels by altering the ventilation pattern because of the resistance, thereby reducing hyper-ventilation. The pneumotach/no-pneumotach order of trials will be counterbalanced.

Subject will not be cooled, and G-suit will be inflated to the appropriate G-suit inflation pressure during all walks. All walks will be at 3.5 mph with visor down, breathing 100% O<sub>2</sub> until a subject reaches one of the limiting criteria:

- a) Completion of 5 min. walk
- b) Upon subject request
- c) Upon reaching 6% inspired CO<sub>2</sub> level
- d) Achievement of 90% of age-predicted HR max.

2) After all instruments are functionally verified, subject will be evaluated in one of the following tests:

Phase I- Immediately after visor-down, subject will walk with (or without, in counterbalanced order) the pneumotach for 5 min, and CO<sub>2</sub> and respiratory rate will be monitored to determine the impact of the pneumotach on performance and inspired CO<sub>2</sub> levels. G-suit will be inflated to 0 or 1.5 psi in counterbalanced order. The two different G-suit inflations will be tested on different days.

Phase II- Subjects will perform 6 min of seated rest immediately prior to walking as in Phase I, except the two G-suit pressures will be 0.5 and 1.0 psi (counterbalanced order). No helmet ventilation will be provided between the rest and walk to simulate an egress evacuation of the shuttle with appropriate CO<sub>2</sub> accumulation prior to the walking phase. The two different G-suit inflations will be tested on different days with order counterbalanced.

Phase III- Replication of Phase II with 0 and 1.5 psi G-suit inflation, in counterbalanced order.

3) Following each Phase walk, the visor will be immediately opened, and the subject will be connected to the suit cooling system.

4) When the subject is ready, she/he will walk again at 3.5 mph at the G-suit inflated to the appropriate pressure for that test Phase, visor up, in order to determine the energy costs of LES/ACES locomotion with the G-suit setting at 0 through 1.5 psi. The additional energy costs of walking with the G-suit inflated can thereby be determined. After this walk which will require approximately 3 to 5 min, subject will again be seated and permitted to recover.

Rest periods between any two test walks will be a minimum of 10 minutes. However, subjects may recover as long as they desire. Liquid cooling and drinking water will be provided during rest.



CO2 will be measured continuously with the Perkin-Elmer mass spectrometer whose analog outputs are connected to a CODAS data collection system. VO2 will be measured with the Aerosport (only in the visor-up configuration). Temperatures will be measured with the Squirrel data collection system. Data collection sheets are shown in Appendix A.

### Preliminary results

A pilot study of LES/ACES helmet CO2 accumulations was conducted on three subjects during June 1996. The first two subjects, "A" and "B" were measured walking with and without the Aerosport mouthpiece and during rest. The complete LES was not worn, but only the neck dam and helmet supplied with 100% O2. The treadmill was elevated to elicit a metabolic rate of 1.7 L/min, similar to the LES with G-suit not inflated (Barrows, et al., 1995), but speed was kept at 3.5 mph. The third subject, "#1" was fully outfitted with G-suit inflated to 1.5 psi. The entire Phase I protocol as proposed was completed with G-suit at 1.5 psi. Findings for the helmet-only simulation are displayed in Table 1.

Table 1. Pilot study results for helmet-only simulation.

Subject (trial)	Inspired CO2 at rest (%):				
	min1	min2	min3	min4	min5
A (w/o pneum)	1.6	1.6	1.8	1.7	1.6
A (w pneum)	1.6	1.7	1.6	1.6	1.6
B (w/o pneum)	2.0	1.8	2.2	2.1	2.0
B (w pneum)	2.0	1.9	1.9	1.8	1.9
Subject	Inspired CO2 during 3.5 mph walk (%):				
	min1	min2	min3	min4	min5
A (w/o pneum)	2.5	2.7	3.0	3.1	3.5
A (w pneum )	2.3	2.9	3.4	3.3	3.2
B (w/o pneum)	2.5	2.9	2.7	2.7	2.8
B (w pneum)	2.3	2.5	2.7	2.9	3.0

The actual LES pilot walk was conducted on 26 June 1996. A full LES inflated to 1.5 psi was used. The subject was healthy, highly fit and experienced in LES use. After 30 sec of visor-down 10 min rest period, CO<sub>2</sub> inspired had risen from a nominal 0.3% (ambient) to an average of 1.6 (sd=0.21)% (regardless of pneumotach use). During the last 2 min of rest, inspired CO<sub>2</sub> was 1.6 ( 0.16) (regardless of pneumotach use). This indicates high test-retest reliability for this phase of testing.

Without the pneumotach, immediately following the 10 min rest period, the subject was able to walk only 100 seconds at 3.5 mph. Average inspired CO<sub>2</sub> over the whole walk was 3.0% (0.84). With the pneumotach, the subject was able to walk only 120 seconds at 3.5 mph. Average inspired CO<sub>2</sub> was 2.3 (0.63)%. Average respiratory rate was 27.3 breaths per min without the pneumotach, and 23.6 with the pneumotach. In both walks, heart rate reached about 160 bpm (84% of predicted maximum). On a previous occasion under the same conditions, this subject was able to walk 300 seconds without the 10 min visor-down rest immediately preceding the walk (from Dalrymple, in progress).

Based upon all these pilot results it was concluded that during the walking part of the test, the pneumotach appears to reduce the inspired CO<sub>2</sub> (by 30%) and respiratory rate (by 16%), and slightly increase endurance (by 20%). Although this effect was not clearly seen in the simulation (Subjects A and B), in the actual LES the pneumotach appears to exert some effect. Both subjects, A and B were able to complete 5 min walk in the helmet alone. Most importantly, in the LES, the 5 to 6 min period which might be expected between visor-down order on the Kennedy Space Center landing checklist and the start of contingency egress could reduce performance capabilities.

#### Expected findings

Based upon the above pilot work and that of previous investigators, it is anticipated that the following will be observed:

a) That inspired CO<sub>2</sub> levels will rapidly exceed 1% under all conditions and will exceed 4% in most subjects during walking. The

rise in CO<sub>2</sub> will be proportional to the metabolic rate. In the EMU, 3 to 8 mmHG of CO<sub>2</sub> with symptoms, or greater than 8 without symptoms, terminates EVA. At EMU pressure (4.3 psi or 222 mmHG), 3 mmHg of CO<sub>2</sub> is equivalent to 1.3%, and 8 mmHg of CO<sub>2</sub> is equivalent to 3.6%. The impact of 1-4% CO<sub>2</sub> on physical performance during LES/ACES walking is unknown.

b) That the use of the Aerosport pneumotach will reduce the ventilation rate such to slow the rate of increase in inspired CO<sub>2</sub> and increase performance.

c) That the metabolic costs of G-suit inflation will be significantly higher and linearly increase with G-suit inflation pressure (i.e. the energy costs of walking with 0.5 psi G-suit inflation will be substantially higher than 0 psi).

d) It is anticipated that a substantial number of rested, fit, 1G-acclimatized subjects will be unable to walk 5 min at 3.5 mph, with the visor down and G-suit inflated to 1.5 psi. The 6 min visor-down rest period will further reduce the walk-completion success rate for all G-suit levels.

## DISCUSSION

Comparisons between the pressure suits worn by military pilots of high-altitude aircraft and US astronauts could be potentially misleading. The USAF SR-71 pressure suit is similar to the LES/ACES. However, the SR-71 suit has no neck dam, and uses a conformal helmet with less dead space and an exhale port near the mouth. The LES/ACES has a neck dam, and uses a non-conformal helmet. Aircrews generally spend the majority of their time sitting quietly and in emergency they eject. In contrast, in contingency egress, Shuttle crews must physically leave the shuttle under their own power. Active egress is a crucial safety issue.

## REFERENCES

Barrows, LH, JJ McBrine, JC Hayes, MD Stricklin, and MC Greenisen. Physiological responses to wearing the space shuttle suit and the prototype advanced crew escape suit compared to the unsuited condition. NASA Tech., Paper 3297

Dalrymple, G, N Packham, MC Greenisen. CO2 distribution patterns in the LES helmet during walking at 3.5 mph. NASA Tech. Paper in progress.

Waligora, JM, K V Kumar, S Freeman-Perez, LL Hnatt and DK Beene. Carbon dioxide washout characteristics of the advanced crew escape suit utilizing a conformal helmet. Unpublished paper, JSC, NASA Dec. 01, 1992.

Waligora, JM, and JH Gilbert. CO2 washout test of the launch and entry Suit. Unpublished paper, JSC, NASA, June 5, 1992.

NASA Doc. #48019, Shuttle entry key cards, p. 4-5, as per Tom Hanson, DT36/BAR, Space Flight Training Division.

Appendix A  
Data Collection Sheet for CO2 Helmet Study Summer 1996

Name \_\_\_\_\_ Date \_\_\_\_\_  
Age \_\_\_\_\_ HT \_\_\_\_\_ in \_\_\_\_\_ cm Wt \_\_\_\_\_ lbs \_\_\_\_\_ KG

G-Suit setting \_\_\_\_\_ psi Resting HR \_\_\_\_\_ bpm  
**6 Min seated rest Visor Down**

Seated HR \_\_\_\_\_ Initial Tre \_\_\_\_\_, Tback \_\_\_\_\_, Tarm \_\_\_\_\_, Tthigh \_\_\_\_\_,  
T calf \_\_\_\_\_

CO2 : min 1 \_\_\_\_\_, min 2 \_\_\_\_\_, min 3 \_\_\_\_\_ min 4 \_\_\_\_\_,  
min 5 \_\_\_\_\_, min 6 \_\_\_\_\_ min 7 \_\_\_\_\_, min 8 \_\_\_\_\_,  
min 9 \_\_\_\_\_, Final \_\_\_\_\_ Final HR \_\_\_\_\_

Subject's Comments \_\_\_\_\_  
\_\_\_\_\_ I

Investigator's Comments \_\_\_\_\_

\*\*\*Recovery Visor-up under some test conditions, immediate walk  
for others\*\*\*

**Walk 3.5 mph 0% grade Visor Down, G-suit inflated \_\_\_\_\_ psi**

Standing HR \_\_\_\_\_ Initial Tre \_\_\_\_\_, Tback \_\_\_\_\_, Tarm \_\_\_\_\_, Tthigh \_\_\_\_\_,  
T calf \_\_\_\_\_

CO2 : min 1 \_\_\_\_\_, min 2 \_\_\_\_\_, min 3 \_\_\_\_\_ min 4 \_\_\_\_\_,  
Final \_\_\_\_\_ Final HR \_\_\_\_\_ Ve Rate \_\_\_\_\_ b/min

Subject's Comments \_\_\_\_\_  
\_\_\_\_\_

Investigator's Comments \_\_\_\_\_

**REST PERIOD- with cooling and visor up**

Time begin \_\_\_\_\_

Seated HR \_\_\_\_\_ Initial Tre \_\_\_\_\_, Tback \_\_\_\_\_, Tarm \_\_\_\_\_, Tthigh \_\_\_\_\_,  
T calf \_\_\_\_\_ Final seated HR \_\_\_\_\_

Time end \_\_\_\_\_ elapsed time \_\_\_\_\_ min

Subject's Comments \_\_\_\_\_  
\_\_\_\_\_

Investigator's Comments \_\_\_\_\_

Name \_\_\_\_\_ Date \_\_\_\_\_

**Walk 3.5 mph 0% grade Visor Down With Aerosport  
pneumotach and nose clip, G-suit inflated \_\_\_\_ psi**

Standing HR \_\_\_\_ Initial Tre \_\_\_\_, Tback \_\_\_\_, Tarm \_\_\_\_, Tthigh \_\_\_\_,  
T calf \_\_\_\_\_  
CO<sub>2</sub> : min 1 \_\_\_\_, min 2 \_\_\_\_, min 3 \_\_\_\_, min 4 \_\_\_\_,  
CO<sub>2</sub> Final \_\_\_\_\_ Final HR \_\_\_\_\_ Ve Rate \_\_\_\_\_ b/min

Subject's Comments \_\_\_\_\_  
\_\_\_\_\_

Investigator's Comments \_\_\_\_\_  
\_\_\_\_\_

**REST PERIOD- with Cooling and visor up**

Time begin \_\_\_\_\_

Seated HR \_\_\_\_ Initial Tre \_\_\_\_, Tback \_\_\_\_, Tarm \_\_\_\_, Tthigh \_\_\_\_,  
T calf \_\_\_\_\_ Final HR \_\_\_\_\_

Time end \_\_\_\_\_ elapsed time \_\_\_\_\_ min

Subject's Comments \_\_\_\_\_  
\_\_\_\_\_

Investigator's Comments \_\_\_\_\_  
\_\_\_\_\_

**VO<sub>2</sub> measured walk Visor UP, G-suit inflated \_\_\_\_ psi**

Standing HR \_\_\_\_ Initial Tre \_\_\_\_, Tback \_\_\_\_, Tarm \_\_\_\_, Tthigh \_\_\_\_,  
T calf \_\_\_\_\_ VO<sub>2</sub> Initial (stand) \_\_\_\_, min 1 \_\_\_\_, min 2 \_\_\_\_,  
min 3 \_\_\_\_, min 4 \_\_\_\_, Final \_\_\_\_\_ Final HR \_\_\_\_\_ Ve Rate  
\_\_\_\_\_ b/min

Subject's Comments \_\_\_\_\_  
\_\_\_\_\_

Investigator's Comments \_\_\_\_\_  
\_\_\_\_\_

LES/ACES Non-Conformal Helmet CO2 Concentrations  
Questionnaire

Name \_\_\_\_\_ Date \_\_\_\_\_

- 1) Did you have any feeling of breathlessness during any phase of testing? Which?
- 2) Did you feel any phase of the testing was particularly demanding? Which?
- 3) Did you have any feelings of anxiety, headache, drowsiness, nausea or any other unusual feelings during any phase of testing? What? Which?
- 4) Did you find any phase of testing physically demanding? Which? What body part?
- 5) Do you have any additional comments regarding this testing?
- 6) Other

